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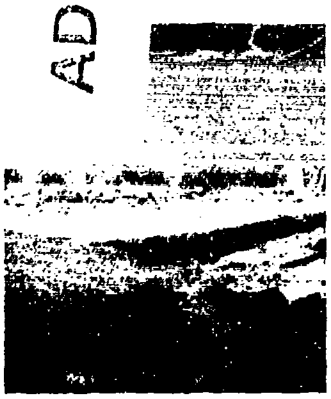

REPAIR, EVALUATION, MAINTENANCE, AND REHABILITATION RESEARCH PROGRAM

TECHNICAL REPORT REMR-GT-3

GEOTECHNICAL ASPECTS OF ROCK EROSION IN EMERGENCY SPILLWAY CHANNELS

Report 3
REMEDIATION

by

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CS	Concrete and Steel Structures	EM	Electrical and Mechanical
GT	Geotechnical	EI	Environmental Impacts
HY	Hydraulics	OM	Operations Management
CO	Coastal		

COVER PHOTOS

TOP Rock protection structure in emergency spillway channel at Black Butte Reservoir (California)

MIDDLE -- Spillway discharge shortly before weir failure at DMAD Reservoir (Utah)

BOTTOM - Results of erosion in emergency spillway channel at Saylorville Reservoir (Iowa)

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REMR research at the US Army Engineer Waterways Experiment Station has established that remediation of unlined emergency spillway erosion damage is a relatively new, but major, concern to the US Army Corps of Engineers (CE) Districts and to other dam owners and operators. The REMR work unit conducting the current investigation has identified numerous CE and other Federal, institutional, and private-sector dams that have experienced erosion damage in their unlined spillway channels. However, only a few projects have implemented or planned remedial and/or preventive measures.

Remediation design is highly site-specific and must be cost-effective, address public safety, and provide continued reservoir operations. Selection of remedial technique(s) must be established by site-specific characterization of the rocks forming an unlined

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19. ABSTRACT (Continued).

spillway channel in terms of rock composition(s), hardness, structural and stratigraphic discontinuities, and precursor erosion elements, all of which determine rock erodibility and its rate. Erosion probability indices based on methods which combine rock mass parameters (composition, hardness, structural discontinuity, etc.), which determine "rippability," with lithostratigraphic continuity may allow for site-prioritization in terms of the need for remedial and preventive techniques.

Potentially useful remedial engineering techniques include cement-based methods such as grouting, shotcrete, soil cement/roll crete, and high-strength unreinforced and reinforced concrete, as well as rock bolts, wire mesh, gabions, and riprap. Potentially useful erosion preventive measures include construction of energy dissipators and cut-off walls and the removal of vegetation and other obstacles to flow. Flow rerouting, the relief of uplift pressures, and the placement of geotextiles and natural grasses (especially in poorly lithified rocks and soils) may also offer useful alternatives. The majority of these remedial techniques have been utilized previously in various erosion protection schemes (e.g., stream banks, canals, levees, etc.); however, their use in unlined emergency spillway channels has not been extensive and there is little documentation available. The selection of a particular remedial technique will depend upon site conditions and costs which are highly variable for a given method.

The present study established a need for more published documentation of performance and effectiveness of remedial measures as well as efforts to predict rock erosion in emergency spillway channels by the use of erosional indices.

PREFACE

This study addresses rock erosion in emergency spillway channels, a problem area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program being conducted by the US Army Engineer Waterways Experiment Station (WES).

This third report of a series summarizes work performed during FY 87. Results of work currently in progress and ongoing research programs will be the topic of further reports to be completed during FY 88 and FY 89. This study was under the direct supervision of Messrs. J. S. Huie, the Problem Area Leader, and Dr. J. H. May, the Principal Investigator, Engineering Geology and Rock Mechanics Division (EGRMD), Geotechnical Laboratory (GL). General supervision was provided by Drs. L. M. Smith, Chief, Engineering Geology Applications Group, EGRMD; D. C. Banks, Chief, EGRMD; and W. F. Marcuson III, Chief, GL, WES.

Mr. James E. Crews and Dr. Tony C. Liu served on the Overview Committee; Mr. Ben Kelly was the REMR Technical Monitor at Headquarters, US Army Corps of Engineers. Mr. William F. McCleese, Concrete Technology Division, Structures Laboratory, WES, was the REMR Program Manager.

This report was written by Drs. C. P. Cameron and D. M. Patrick, Department of Geology, University of Southern Mississippi, Hattiesburg; Mr. C. O. Bartholomew and Dr. A. W. Hatheway, Department of Geological Engineering, University of Missouri, Rolla; and Dr. J. H. May, EGRMD, WES. The report was edited by Mrs. Joyce H. Walker, Information Products Division, Information Technology Laboratory, WES. The helpful comments and contributions of District hydraulic and geotechnical engineers as well as those from individuals in the private sector are appreciated by WES.

COL Dwayne G. Lee, EN, was Commander and Director of WES. Dr. Robert W. Whalin was Technical Director.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
acres	4,046.873	square metres
acre-feet	1,233.489	cubic metres
cubic feet	0.02831685	cubic metres
cubic yards	0.7645549	cubic metres
degrees (angle)	0.01745329	radians
feet	0.3048	metres
inches	2.54	centimetres
pounds (force) per square inch	6.894757	kilopascals
square feet	0.09290304	square metres
square yards	0.8361274	square metres
tons (2,000 pounds mass)	907.1847	kilograms

GEOTECHNICAL ASPECTS OF ROCK EROSION IN EMERGENCY SPILLWAY CHANNELS

REMEDIATION

PART I: INTRODUCTION

Background

1. Prediction of initiation, rate, and intensity of erosion in earth materials is not a precise science, and a significant amount of erosion-induced damage has occurred in unlined emergency spillway channels at flood-control and water-storage projects built and managed by the US Army Corps of Engineers (CE), other Federal agencies, state, and local interests. The potential exists for severe erosion of the rock and associated soils flooring of unlined emergency spillways to cause undermining or failure of spillway structures and catastrophic release of reservoir waters, damage to dam embankments, spillway channel bank failure, and sedimentation in the spillway exit and main channel. Therefore, the CE was prompted to include this problem as a work unit in the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program being conducted by the US Army Engineer Waterways Experiment Station (WES).

Objectives

2. The objectives of this work unit include the following:

a. To identify and document the geotechnical and hydraulic factors influencing the rate and mechanism of erosion in unlined emergency spillway channels.

b. To identify and document channel response to emergency spillway flow and to assess the nature, magnitude, and severity of downstream impacts.

c. To develop methods of predicting erosion in unlined emergency spillway channels.

d. To develop cost-effective remedial and preventive measures to minimize the problem of severe erosion in unlined emergency spillway channels.

e. To maintain and continually update an observational data base which documents important erosive spillway overflow events at CE projects.

f. To provide timely technology transfer in this problem area to CE personnel and other interested parties in Federal, state, and local agencies.

Scope

3. Geotechnical factors control the selection of appropriate cost-effective remedial and preventive engineering techniques capable of minimizing existing and potential spillway channel erosion, maintaining the integrity of spillway structures, and reducing downstream impacts. This report is primarily dedicated to addressing remediation of erosion in rock; however, selected remediation measures for soils and overburden are also presented since these unlithified materials are usually closely associated with rock in emergency spillway channels. This report, the third in a series, provides documentation and assessment of remedial measures implemented (or contemplated) to solve or impede erosion in emergency spillway channels. The combined results of research conducted during FY 86 provide the rationale for proposing new methods of predicting erosion in unlined emergency spillway channels.

4. These reports are intended to serve as a mechanism for communicating research results, ideas, and concepts to interested CE personnel and their counterparts in other Federal, state, and local agencies. CE District experience, case histories, and site visits, as well as technical input from other concerned agencies, continue to provide vital elements of the working observational data base and serve as the foundation for development and refining of research tasks.

PART II: PREDICTION AND REMEDIATION

Overview

5. Selection of an appropriate, cost-effective remedial technique at an emergency spillway involves a number of alternatives. Remedial action options range from a "do nothing" alternative, to expensive blankets of reinforced concrete covering the entire spillway discharge channel. Choosing the most appropriate combination of technologies for a given spillway is further complicated by hydraulic design variables, geotechnical conditions, public safety, downstream impacts, and the importance and present use of the reservoir.

6. Emergency spillways are designed to protect the main embankment during peak flood conditions. Spillway failure can lead to catastrophic loss of reservoir waters. At many locations, loss of stored water would not have presented a serious problem at the time of construction. However, urbanization has occurred downstream of many dam sites, and many reservoirs have become a major source of water, hydroelectric power, and income through recreational use. Loss of storage may result in loss of life at some locations, destruction of property, water shortages, and loss of revenue.

7. Remediation design is therefore highly site-specific and must be cost-effective, address public safety, and provide continued reservoir operations. Optimal remediation design will provide, in some way, for all of the design variables weighted against site-specific factors and conditions. If this is not accomplished and remediation is performed strictly on the basis of past project experience or with excessive factors of safety, then either money will be wasted or safety will be compromised. A tailor-made remedial plan should not only save money, but provide a high degree of safety and performance.

8. To create this tailor-made plan, the engineers and geologists involved in remediation work must obtain all of the site and areal geologic information, determine geotechnical conditions, consider the hydrologic setting and the hydraulic characteristics of the structure and discharge channel, and consider the implications of the interrelationship of each set of these characteristics. Along with this, the remedial team (composed of hydraulic, civil, and geological engineers as well as geologists) must consider

downstream impacts and reservoir use. After assessing all of these elements and the implications of their interrelationship, then an appropriate cost-effective remedial plan can be formulated.

9. One important option in emergency spillway remediation that is not available in most other engineering projects is that the remedial structure or structures need not always be permanent. "There are situations due to rarity of major events or other site-specific conditions where it may be justified to construct a remedial structure that will be destroyed by that major event. Such a situation presents itself when several of these lesser structures can be constructed and reconstructed for the cost of one structure that will withstand the major event without damage to the dam or reservoir" (California Department of Natural Resources 1974).

10. An example of this type of situation occurred at the Bridgeport Dam in California, where hydrologic investigations showed that the emergency spillway needed to be enlarged--a responsibility of the Walker River Irrigation District (California Department of Natural Resources 1974). The major problem in enlarging the emergency spillway was the fact that it was constructed in highly erodible glacial till, and that it was unlined. "Low-cost concrete sills were installed to provide erosion protection" (California Department of Natural Resources 1974). These structures were justified even though they would be substantially damaged during a flow event and thus require repair; however, they would retard the rate of channel erosion and protect the main embankment. This measure was further justified by the fact that the structures could be repaired or replaced several times with the cost being substantially less than it would be for completely lining the spillway with concrete. Options like the "impermanent structure" must be considered when designing a remedial plan for an emergency spillway.

11. Another important consideration during emergency spillway remediation is the fact that all remedial structures must withstand a number of different forces. Many of these structures will be able to withstand the direct forces of erosion but unable to withstand indirect forces such as undercutting. Therefore, when considering remedial options for emergency spillways, all of the possible effects of erosion must be addressed.

12. For large projects, which includes most of the CE dams, it may be very expensive to employ preventive or remedial measures. Due to this fact, scale and/or numerical models might be considered to assist in determining the

effects of employment of various measures. Proper use of such models can create a great cost savings as well as providing a data base for more effective employment of engineering techniques. However, it should be remembered that model studies cannot be effectively undertaken until after thorough hydrologic, hydraulic, and geotechnical characterizations have been performed. The models should be designed not only to reflect site hydrologic and hydraulic characteristics but should also be designed in such a way as to adequately represent the geotechnical and geologic properties of the site.

13. Many effective model studies have been carried out at WES. One such study dealt with a scale model (Murphy and Cummins 1965). This study was performed to determine the different effects of various remedial technologies on arresting the erosion that had occurred downstream of the spillway at Miraflores Dam in Panama. By employing a model study, it was determined "that adequate protection would be provided by addition of a stilling basin consisting of a 40-ft-long* apron terminated by a 3-ft-high dentated end sill" (Murphy and Cummins 1965).

14. The major advantage of a model study comes from the fact that many different combinations can be tried for a relatively small expense, especially if numerical models are being used.

Erosion Prediction

15. Because the CE manages too many projects for each to be evaluated individually, Cameron et al. (1986) recommended development of potential methods and techniques which could be used at District levels to force-rank or prioritize unlined emergency spillway channels in terms of their erodibility. Using such methods, problem sites could be identified early and treated promptly. The same authors proposed that the rock-mass parameters that govern rippability, when combined with lithostratigraphic continuity factors, may provide predictive erosion indices from a geotechnical point of view.

16. Rippability is a form of rock-mass classification, or rating, that enhances engineering judgment with respect to the assessment of the excavation characteristics of earth materials and bulldozer or backhoe ripping capability

* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

(Weaver 1975 and Headquarters, US Army Corps of Engineers (HQUSACE) 1970, 1983). The rock-mass parameters from which a rippability rating (RR) is derived include rock type, hardness, weathering, structure (strike and dip orientation, joint spacing and continuity, fracture, cleavage), and fabric. Seismic P-wave velocity has also been found to be an index of rippability when used judiciously on a comparative basis with RR.

17. Assessment of rippability may be useful from the standpoint of assessing rock erodibility (especially with respect to the scale of hydraulic forces acting on unlined channels during CE spillway overflow), because it combines rock-mass aspects highlighting discontinuities of earth materials.

Structural and
stratigraphic discontinuities

18. The influence of structural and stratigraphic discontinuities on erosion processes affecting unlined spillway channels is noted in EM 1110-2-1603 (HQUSACE 1965) and also discussed in Cameron et al. (1986). A more complete discussion of this topic is contained in Cameron et al. (in preparation). The authors emphasize the concept that discontinuities in earth materials often control the location and geometry of channel gradient changes (knickpoints) which can occur as abrupt waterfalls, a series of closely spaced "stairsteps," or gentle, subtle changes. Such changes are often influenced by large-scale (a few metres) stratigraphic and structural discontinuities such as stratigraphic pinchouts (e.g., sandstones wedging out abruptly against shales), faults, fractures, jointing of bedrock, igneous contacts, veins, and solution cavities such as those common to carbonate and evaporite rocks.

19. Detailed engineering geological maps and cross sections which provide maximum understanding of the nature and distribution of discontinuities in the rocks underlying emergency spillway channels are essential to meaningful evaluation of erosion potential (particularly headcutting) at site-specific levels.

Definitions and classifications

20. Murphy (1985) defines "discontinuity" as all perceivable breaks or divisions in a rock mass. Strictly speaking, this definition embraces any interruption in lithologic and physical properties (e.g., mineralogy, rock fabric, structure, etc.) and would therefore encompass features observable only on microscopic scales such as microfractures. However, as pointed out in Cameron et al. (1986), severe channel response to emergency spillway flow,

particularly in CE spillway channels, appears to be governed more by discontinuities which occur on a megascopic scale rather than on a microscopic or grain-to-grain basis. To maintain consistency in usage, definitions of specific types of discontinuities discussed in the following sections are those given in Glossary of Geology, (American Geological Institute 1987).

21. It is possible to classify discontinuities under two broad headings--structural and stratigraphic. Structural discontinuities can occur in all rock associations and are caused by movements resulting from natural compressive and tensile stress fields which affect rock masses in the upper crust of the earth. The resulting rock deformation produces folds, fractures, faults, joints, and, in the case of some orogenic belts, regional metamorphism and the forceful injection of molten rock and other fluids. Depending on the rock associations involved at a given crustal level, these processes can result in variable orientations of such planar structural elements as stratal dip, schistosity, foliation, formation of igneous contact zones, and veins, all of which have significance as important structural discontinuities from an engineering point of view.

22. Stratigraphic discontinuities are usually limited to stratified rock sequences (sedimentary rocks) including those hosting or admixed with volcanic igneous rocks (lavas, tuffs, volcanic breccias, and volcano-clastic sedimentary rocks). Stratigraphic discontinuities include depositional features such as bedding planes, bed contacts, unconformities, sedimentary structures and textures as well as bed pinchouts and facies changes within the same lithostratigraphic unit.

23. Dissolution pits, cracks, and cavities result from chemical weathering and erosion and comprise a special type of discontinuity. Although most common in carbonates (limestones and dolomites) and evaporites (gypsum, anhydrite, salt, etc.), dissolution features can also occur occasionally in other rock associations as well.

24. Faults and rapid changes in dip orientation (tight folding), stratigraphic pinchouts, rapid facies changes, and unconformities are of considerable importance when present in an unlined spillway channel in that these features often juxtapose rocks of widely varying competence and resistance to erosion. For example, at Grapevine Spillway (near Dallas in the CE Fort Worth District, Texas) the pinchout of a moderately bedded sandstone unit controlled the location of a channel gradient change (knickpoint). The steepened

downstream reach, being underlain by soft, weathered, erodible shales, reacted negatively to the first spillway flow event in 1983. Rapid undercutting of the shale substrate resulted in collapse of the sandstone layer and headward retreat of the knickpoint. A large stilling basin was constructed at a cost of $10 million to inhibit further headcutting during emergency spillway overflow. Other cases are cited in Cameron et al. (1986).

25. Lithostratigraphic continuity is a key factor controlling the rate and intensity of spillway erosion in stratified rock sequences. Rapid changes in lithostratigraphic facies, both laterally and vertically, appear to control the location and rate of headward retreat of knickpoints and waterfalls and locally maximizing hydraulic energies and scour intensity. Cameron et al. (in preparation) discuss controls of lithostratigraphic continuity and propose that modern methods of facies analysis allows for intelligent estimates of facies variability and lithostratigraphic continuity on both regional and local scales.

26. If structural and stratigraphic discontinuities are to be used effectively in the evaluation and prediction of bedrock erodibility in unlined emergency spillway channels, then rigorous attempts must be made to accurately describe and quantify the features discussed above. Comprehensive methods for describing and quantifying the rock mass features described above are given in Murphy (1985).

Erosion Probability Index

27. The idea that an "Erosion Probability Index" (EPI) can be generated for a given unlined emergency spillway channel is based on the concept that the key geotechnical factors controlling erosion during spillway flow are contained in rock-mass rippability and lithostratigraphic continuity and that these factors can be quantified or assessed in a semiquantitative manner. Assuming that the methods and techniques used to assess rock-mass rippability and lithostratigraphic continuity are applied uniformly and consistently in spillway channel evaluations, it should be possible to force-rank spillway channels in a given District based on their EPI values. This approach will assist establishing priorities for channel remediation, at least from the geotechnical standpoint.

28. The major assumptions which govern the application of this approach are:

a. All weighting processes and probability estimate methods have limitations.

b. There are no universal formulas. Detailed site-specific evaluations are prerequisite to the successful application of this method.

c. All CE unlined emergency spillway channels will undergo future flow events. Lack of previous flow events should never be an upgrading factor in terms of geotechnical evaluation of bedrock erodibility.

d. Data are based on measured parameters. Judgmental interpretations are based on empirical observations and experience. Data and judgmental interpretations are both valid and necessary criteria in site-specific evaluations.

e. Uniform and consistent methods of spillway channel evaluation will be applied within a given District. This assumption requires that the geotechnical data base for each spillway channel be complete and that data quality is uniform throughout the District.

f. Where facility safety is a real concern, conservative interpretations should prevail; particularly with respect to subsurface correlations based on wide-spaced borehole control.

29. The proposed method for calculating a geotechnical EPI (EPI_g) is illustrated in Table 1. The rating values used are illustrative only; individual Districts should attempt to establish their own rating changes and factor weightings based on local experience as to which factors exert major erosional controls. For example, rock weathering varies in character and intensity as a function of both rock type and climate and may be expected to be weighted differently over state, provincial, or national areas.

30. From the standpoint of rock erosion in unlined emergency spillway channels, rock masses with low RR values are easily excavated by conventional rippers (tractor- and bulldozer-mounted narrow profile instruments), and are also those expected to be relatively nonresistant to the high hydraulic stresses prevailing during spillway overflow events. At the other end of the spectrum, very high RR can imply that the rock can only be excavated by blasting. Such rock masses are often highly resistant to erosion. For example, the exposed, hard sandstone ledge which floors the upper portion of the unlined channel at the Saylorville (Iowa) spillway still bears the elongate scars of a futile attempt to rip and excavate the channel to uniform grade during dam construction. When ripping proved impossible, a decision was made

Table 1

Geotechnical Erosion Probability Indices (EPI_g)

Rippability Parameters (E_r)

Parameter	Rating*
Rock mass parameters	
Rock hardness	0-10
Rock weathering	1-15
Joint spacing	5-30
Joint continuity	0-5
Joint separation	1-5
Strike/dip	3-15
Seismic P-wave velocity	5-20
Total rating	15-100

Continuity Parameters (E_c)

Vertical continuity (bed thickness)	5-15
Lateral continuity	5-25

$$EPI_g = E_r + E_c$$

E_r = rippability (sum of weighted rock mass parameter ratings and seismic wave velocity)

E_c = lithostratigraphic continuity (sum of vertical and lateral bed/rock unit continuity ratings

* Illustrative purposes only.

to leave the sandstone in place as a flooring for the upper portion of the unlined channel rather than go to the expense of a drill and blast excavation exercise. The resistant sandstone body proved to be relatively nonerodible and impeded serious headcutting during the 1984 flow event (Cameron et al. 1986).

31. Seismic P-wave velocity should be used with caution in estimating rippability. HQUSACE (1983) recommends that seismic wave velocity be used with caution in estimating rippability--further stating "When data can be obtained on the parameters required for use of the rock-mass rating or other similar systems in rippability assessment, their use will supplement an assessment using only seismic data and rock type and should enhance overall engineering judgment."

32. Hydraulic factors controlling erosion during emergency spillway overflow were studied by the WES Hydraulics Laboratory. Both geotechnical (EPI_g) and hydraulic (EPI_h) indices should be used in the final rankings of unlined spillway channels in a given District, for example;

$$EPI = EPI_g + EPI_h$$

PART III: REMEDIATION METHODS

Objectives of Remediation

33. Remediation efforts should be designed to minimize, reduce, or to obviate spillway erosion while meeting the necessary primary hydraulic design criteria for passage of flood waters. The primary determination as to how much water must be accommodated during Probable Maximum Flood (PMF) is the responsibility of the hydraulic engineer(s). Following this determination, the spillway surface should be evaluated as to what remedial engineering measures will be required to maintain the spillway under PMF conditions, or portions thereof.

34. PMF or Spillway Design Flood (SDF) estimates have little relation to the ability of rocks and soils forming the floor of an unlined emergency spillway channel to withstand the erosive impact(s) of spillway overflow. PMF and SDF estimates are used in the hydraulic design of the spillway structure. These hydraulic parameters do not consider the geotechnical aspects of the unlined spillway channel, and, hence, have no bearing on its erodibility. Case histories at CE and other projects provide ample proof that severe channel erosion can occur during the overflows which represent only small fractions of the project PMF or SDF (Cameron et al. 1986). For example, overflow representing 9 percent of design discharge caused severe erosion of the rocks underlying the unlined portion of the Saylorville, Iowa, spillway during June-July 1984. Three overflows in the range 4 to 8 percent of design discharge caused considerable erosion in the Lake Brownwood (Texas) spillway. The 21-day overflow during 1981 at the Grapevine (Texas) spillway reached only 5 percent of design discharge, yet produced severe, rapid headward erosion in the channel, and a rugged erosional landscape developed downstream with up to 30 ft of local relief.

35. Remediation techniques for unlined emergency spillways rely on the ability of spillway channel earth materials to resist erosion. This must be established by site-specific identification of material properties or characteristics that would lead to erosion. This determination is followed by consideration of remedial measures to strengthen the spillway material(s) at points susceptible to erosion.

36. Suitable remedial methods can be devised for virtually every spillway, but most cases will retain an element of uncertainty as it relates to the factor of safety and risk assessment in achieving remediate goals. The uncertainty relates to characterization of site geotechnical factors as well as the selection of design-related variables and the inadequate quantitative prediction methods for rates of erosion or headward migration of erosion. These factors, strength, abrasive resistance, and chemical stability of remediated earth materials must be determined in terms of the hydraulic stresses generated by spillway overflows.

Factors of Safety

37. An important goal in the selection and design of remediation should be the computation of a factor of safety for the performance of each designed remedial method. Factors of safety, considering strength alone, may be calculated for spillway slopes either with or without remediaton. The factor of safety should also incorporate the additional remedial strength, abrasion resistance, and chemical stability (sum of resisting forces) afforded by the remediate method and which are opposed by the sum of the hydraulic (driving) forces acting on the channel. However, uncertainty is inherent in terms of calculating both resisting and driving forces. The uncertainty derives from our inability to calculate either theoretical or empirical values for the erosion resistance of remedial measures due to the absence of a base of theoretical knowledge on erosion resistance and a lack of sufficient experience and case histories pertaining to the success or failures of the various remedial measures. Further uncertainty involves the calculation of the hydraulic driving forces acting on the channel. Current experience at CE dams indicates that severe erosion has occurred at spillway discharges which were merely fractions of the PMF (Cameron et al. 1986). Preliminary laboratory and additional field investigations have verified these occurrences of erosion at low discharges and explained them in terms of spillway geometry and thresholds (Cameron et al. Report 2 of this series (in preparation)). Thus, factors of safety for remediation cannot be calculated at this time.

Remedial and Preventive Measures

38. Measures are designated as remedial or preventive based only on the time of application; that is, whether the measure used before or after the spillway channel has been damaged.

39. Each of the measures to be discussed represents a technology, or set of technologies, that are well proven in a variety of engineering applications. However, some of the remedial measures to be recommended herein have not yet, at least within the knowledge of the present authors, been well documented for use in emergency spillways. Those technologies that are not well documented for use in emergency spillways are measures which the authors believe can provide viable and cost-effective alternatives at many emergency spillway locations.

40. During the present study, the authors found a need for more published documentation of the effectiveness of different remedial measures for emergency spillways. Although the authors have conducted a thorough literature search and have consulted the CE data base, as well as those data bases for other Federal dams, there is very little published information on remedial engineering. Also, there is very little published information on state, private, or local interest dams, even though we suspect that there may be a number of successful case histories for some of these dams, which have not been formally published.

Reservoir reregulation

41. Reregulation should be considered as a temporary means of reducing the potential for erosion of unlined emergency spillway channels. This simple act entails lowering the reservoir, prior to the flood season, so that the emergency spillway may either not experience flow or so that such flow may be at velocities and heads less than those estimated to initiate erosion.

42. This approach is particularly appropriate whenever the emergency spillway has been previously damaged by flood flows, has a significant potential for such damage, or is awaiting or undergoing remediation (e.g., Black Butte Dam, California, Sacramento District). In all cases, reregulation is a temporary (yearly) solution to a recurring problem. Reregulation cannot be applied to dams at which the service and emergency spillways are one and the same, or to dams that have been built without mechanical regulatory structures.

43. Reregulation is often not an acceptable, long-term solution to a real or perceived erosion problem at the emergency spillway. For those reservoirs that serve as flood regulation facilities, this approach is conservative to the degree that it provides additional reservoir storage capability and therefore reduced potential for negative downstream impacts. For those reservoirs that also serve as irrigation storage, this form of protection may be unacceptable, in that the protective, empty storage volume may not be replenished by wet-season runoff, and the irrigation function may not be met. In this case, the portion of the available reregulation storage may be limited to the degree that irrigation demands may still be met on a low-precipitation basis. Reregulation may also be unacceptable where the dam serves to maintain a navigation pool or is primarily for hydropower poses.

44. Costs associated with adoption of reservoir reregulation are entirely related to secondary impacts related in turn to the function of the reservoir. Unlike costs associated with remedial engineering of emergency spillways, these cannot be linked directly to specific unit, nor can such costs be directly estimated. The actual costs of implementing reregulation are contained in the normal operating budget of the reservoir, being mainly associated with manpower required to monitor storage volumes and rates and to operate control structures (Table 2).

Table 2

Cost Factors Related To Reregulation

Secondary Impacts	Function of Reservoir
Crop loss	Insufficient irrigation storage
Recreation inactivity	Insufficient water to provide boat ramp access, boat movement, and access to fishing grounds
Erosion and siltation	Water level reduced to elevations producing erosion and sedimentation within the reservoir body (and upstream due to lowering of local base level resulting in increased erosional energy in the watershed)
Loss of wildlife habitat	Nesting for aquatic birds and a reduction in living space and spawning areas for fish and other aquatic life forms
Hydropower and water supply loss	Water levels reduced leaving insufficient head to supply power and water

45. One example of reregulation occurred at the Brooktrails No. 3 North Dam in Willits, California, where the reservoir is used for domestic water supply (Redlinger et al. 1975). At this location an old landslide threatened to block the spillway. One of the first immediate remedial measures was to empty the reservoir--a type of reregulation. After the reservoir was empty, permanent repair, consisting of a series of drains, was carried out.

Cement-based remediation

46. Concrete and various other portland cement-based pavings are traditional lining materials for a wide variety of spillway channel construction and repair applications. In addition to its use as a reinforced lining blanket, options such as lean concrete, shotcrete, high-strength mixtures, grouting, dental concrete, and rollcrete are available. One great advantage to cement-based remediate techniques is that most of them tend to reduce or eliminate the possibility of rock plucking occurring within the emergency spillways and their unlined channels. Due to its extensive technological development, concrete is often the first and sometimes only measure considered in construction and/or repair of emergency spillways and their unlined channels. There are many situations in which a concrete application will be the best choice, both from the standpoint of cost and from hydrological and geotechnical/geological characteristics. However, there will be many situations where these same factors create conditions which make concrete cost-prohibitive or structurally inappropriate.

47. Most cement-based remediation techniques are those that are applied by workers and/or machines directly to the area of the emergency spillway requiring attention. An alternative use of cement-based materials is in grouting, in which the cement-based material is delivered to a remote point or place of application by borehole injection mainly along rock discontinuities.

Grouting

48. Grout is a cement- or chemical-based mixture generally placed in voids and open discontinuities that cannot normally be reached by workers or equipment. Portland cement grout is a traditional dam construction material that is generally used to consolidate a mass of rock; whereas, chemical grout is used as a primary means of soil consolidation. Both will help in forming a barrier to ground water flow. As applied to remediation of unlined emergency spillway channels, cement-based grout would serve primarily to consolidate or

strengthen an entire rock mass. The consolidation takes place by grout filling the open voids or discontinuities, thereby removing treated discontinuities as low-strength features susceptible to plucking or other forms of erosion. A secondary advantage of grouting is that, when properly applied, grout will strengthen the entire treated rock mass and provide an increase in the overall strength of the rock mass. A tertiary advantage is that, once consolidated, a grouted rock mass will likely not be subject to uplift forces, possibly against even the maximum flood discharge that can be accommodated by the spillway channel.

49. Grouting has an inherent problem in application to remediation of emergency spillway channels. Grout injection requires pressurization of rock intervals below the ground surface. Most spillway channel remediation needs call for consolidation of the exposed and very near-surface (usually the uppermost 3-4 m) spillway channel material and would involve procedures very similar to consolidation grouting for foundations (Table 3).

Table 3

Conditions for Employment of Grouting

Applied to uppermost few metres of spillway surface.
Can serve as final flow-resistant surface where adjacent intact rock is erosion-resistant.

Lean concrete

50. Lean (low cement content) concrete is a low-cost void-filling material for conditions where high structural loads are not present. Most lean concretes are mixed with fine sand aggregate and cement in sufficient quantity to assure an easily placeable viscosity and ease of movement into voids and open discontinuities. Typical compressive strength of such lean mixtures averages 10 to 20 MPa (1,500 to 3,000 psi) for most applications.

51. The sole purpose of lean concrete should be to fill voids and open discontinuities, and to prevent plucking, which will increase erosion resistance. Typical remediation uses of lean concrete would be to fill open structural discontinuities in the channel bottom where the lean concrete infilling will be capped with erosion-resistant material. Even this erosion-resistant layer will not require expensive, high-strength concrete or

large-aggregate mixtures, as flood bedloads in emergency spillways are small, due to clear water releases at the crest (Table 4).

Table 4

Conditions for Employment of Lean Concrete

Bulk filler not exposed to erosive forces.
Open-fracture filling.

Shotcrete

52. Shotcrete refers to a specific mixing and placement method for pneumatically applied surficial mortar. Dry-mix mortar components (cement and aggregate) are fed to the application gun and mixed together with water prior to being projected through a nozzle equipped with a perforated manifold. This sprayed concrete can be placed with a low water-cement ratio, and therefore can achieve a high compressive strength (Merritt 1968). The term gunite is synonymous with shotcrete, but is not preferred as it stems from proprietary sources. Shotcrete may also be applied as a wet-mix.

53. Design uses of shotcrete should be based on achievement of sufficient compressive strength to represent erosion resistance and to serve in whatever rock mass reinforcing role it has been assigned (Table 5).

Table 5

Conditions for Employment of Shotcrete

Applied to exposed inclined surfaces.
Not a primary channel surface material.
Must be protected from uplift pressures.
Must not be applied over areas of variable compressive strength.

High-strength concrete

54. High-strength, reinforced or unreinforced, concrete refers to various mixtures of concrete that provide added abrasive resistance and compressive strength. These mixtures may consist of the basic concrete mixture

with the addition of silica fume, a high-range water reducer, providing a lower water/cement ratio and a hard aggregate.

55. High-strength concrete was placed in the stilling basin of the Kinzua Dam (Pennsylvania) that had experienced "severe abrasion-erosion." Silica-fume and limestone available near the site proved suitable and cost effective (Holland et al. 1986). Repair concrete met a 28-day compressive strength of 86 MPa (12,500 psi) and also had the required abrasion-erosion resistance.

56. The result of a companion study (Holland 1983) showed that the performance of aggregates cannot be determined from the rock name or classification. Samples with diabase and gabbro aggregate had the same erosion resistance as a sample with limestone aggregate. "The answer to this apparent anomaly lies in the difficulty of attempting to prejudge the performance of an aggregate based upon a rock name. The resistance of an aggregate to abrasion-erosion damage is apparently closely related to the hardness of the aggregate" (Holland 1983). Hardness is not dependent upon rock name or classification. It is dependent upon such factors as cement type, grain size and type, weathering, etc.

57. Erosion resistant concretes made from silica fume and high-range water-reducing admixtures (HRWRA) will perform as well as polymer concretes (PC), polymer UCP portland-cement concretes (PPCC), and polymer-impregnated concretes (PIC), and will be less expensive and easier to produce and install (Holland 1983). However, "The use of a silica-fume concrete will require careful control and inspection. The batch plant will have to be capable of handling the silica fume in whatever form it is made available by the producer (slurry or dry). To achieve the full benefits of the silica fume, it will also be necessary to use a high-range water-reducing admixture (HRWRA)" (Holland 1983), which is a polymer additive that increases workability and particle contact (Elifrits 1987*). "The use of an HRWRA will raise the problems normally associated with these products, particularly slump loss versus travel time from the batch plant. Overall, it must be recognized that a silica-fume concrete is a sophisticated material that will require greater than normal care and inspection" (Holland 1983). If time and financial

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* Personal communication, 1987, C. D. Elifrits, Associate Professor of Geological Engineering, University of Missouri, Rolla.

constraints, or other site-specific conditions, do not allow for this greater care and inspection, "It would be better to select a more conventional concrete for the repair material" (Holland 1983).

58. Silica-fume concrete is especially effective in withstanding abrasion-erosion. At most emergency spillways, overtopping of the spillway structure involves a "clear water release"; i.e., waters entering the spillway discharge channel do not contain a bedload or suspended load. Abrasion-erosion of emergency spillway channels during a flow event is not likely to occur except in the downstream portions of large channels. The use of silica-fume concrete would only need to be considered for the downstream portions of the emergency spillway channel and not for other areas except in special circumstances. If the entire spillway channel is to be lined, thus removing the source of abrasive material, it would be unnecessary to use silica-fume concrete in any portion of the spillway channel (Table 6).

Table 6

Conditions for Employment of High-Strength Concrete

A primary means of resisting erosion forces.
Reinforced or unreinforced.
Most expensive of concrete-based treatments when used over large areas.
Must consider deformation moduli of underlying geologic materials.
Must have drainage provisions to resist uplift pressures.

Soil cement and rollcrete

59. Cement has long been used as an additive to stabilize and strengthen soil and overburden to serve as a bearing substratum for roads and airfields. Small percentages of cement are added and mixed with soil prior to compaction. The technique has been extended over the past decade to use in major dam embankments as rollcrete (roller-compacted concrete). This technology is now a well-accepted innovation. One of the remediate measures considered for use on the emergency spillway at Sam Rayburn Dam, east Texas, involved a 60-cm (24-in.) blanket of rollcrete over the first 700 m (2,000 ft) of the emergency spillway channel. This alternative would cost approximately $62 million; however, some damage to the emergency spillway would still occur during passage of the PMF (Cameron et al. 1986) (Table 7).

Table 7

Conditions for Employment of Soil Cement/Rollcrete

Not generally considered for primary resistance to erosion.
Used to fill in relatively large voids.
Must have accessibility for placement.
Has relatively high shear strength and very low compressibility when placed in thick (say more than 1 m) bodies.
Employs cement 8 to 12 percent range, as an additive.
Applicability limited to soils/overburden and very weak rock.

Reinforced concrete

60. Reinforced concrete has been in use for a long time in hydraulic structures. It is particularly used for constructing portions of concrete gravity dams, spillway weirs, and also for the aprons below such weirs. Due to the fact that this method involves the use of large amounts of reinforcing steel, which must be installed prior to placement of the concrete, it is second in expense to high-strength concrete. Due to the large size of most emergency spillways at CE dams, it would be cost-prohibitive to consider using reinforced concrete to line the entire spillway channel. One example of the great expense that can be encountered when using reinforced concrete is at Sam Rayburn Dam in east Texas. At this location, one of the proposed remedial measures involves the placement of a 43-cm (18-in.) blanket of reinforced concrete over the first 700 m (2,000 ft) of the unlined emergency spillway channel at an estimated cost of $85 million. Even at this great expense, passage of the PMF could still fail the spillway weir, while smaller "flows might result in extensive damages to the channel" surface (Cameron et al. 1986). Keeping this example in mind, it is recommended that reinforced concrete only be considered for use in small portions of the spillway channel.

61. Another factor which must be kept in mind when considering reinforced concrete in remediation is that it is only effective as long as the flow passes over the top. If flood waters are able to flow beneath a reinforced-concrete section, failure will possibly occur due to the removal of the subgrade material by floodwaters. A similar type of failure can occur at the outlet portions of an emergency spillway when steep slopes or cliffs exist

below a reinforced-concrete section. This type of failure occurs due to turbulence at the bottom of a steep channel section causing undercutting (Table 8).

Table 8

Conditions for Employment of Reinforced Concrete

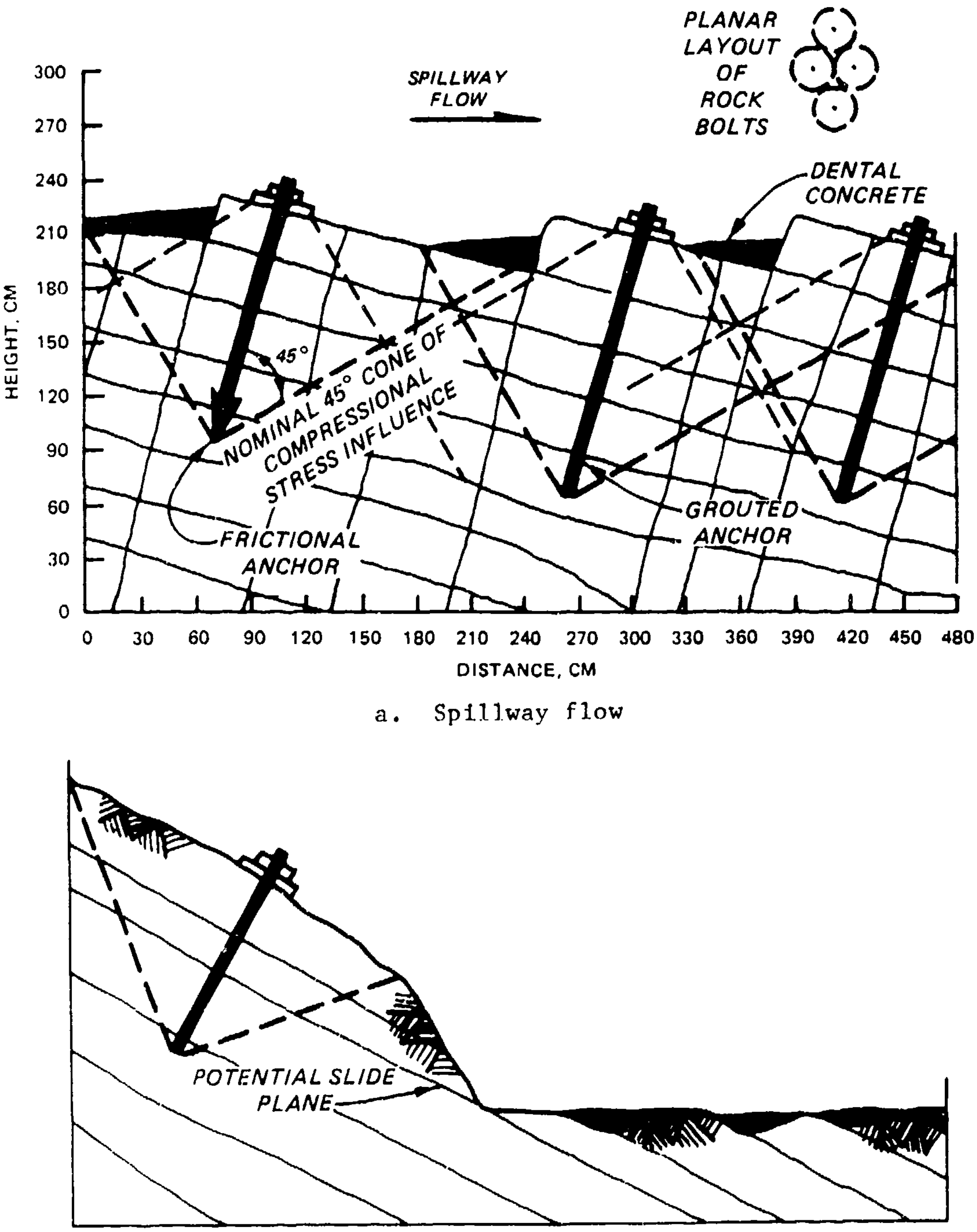
As primary resistance to erosion.
Often proves to be very expensive.
Can be used to span bodies of earth materials having a wide range of deformation moduli.
Offers highest assurance of erosion resistance, under conditions of proper placement.
May be susceptible to undercutting erosion.

Dental concrete

62. The application of dental concrete is a technique which generally uses high-strength concrete to fill in irregularities on excavated and sound bedrock of core trenches for concrete gravity dams as well as other types of dams. The technique is generally applied directly to joint-bounded surfaces to produce a high-integrity bond between rock and concrete. This same technique is basically applicable to remediation at emergency spillways in which the high-strength concrete is used to fill in joint-bounded surfaces on dipping, jointed bedrock.

63. The resulting smooth channel surfaces are designed to keep the water from flowing into open joints and creating uplift forces that can force apart and separate individual joint blocks for plucking. As shown in Figure 1, erosion susceptibility is greatest when discontinuity strikes are approximately perpendicular to the channel axis, and when the primary (most persistent = continuous) joint set or bedding dips downstream. Plucking-type erosion can still occur, however, when the primary discontinuity dips upstream.

64. Dental concrete can be beneficial when used in conjunction with rock bolts (see Figure 1). Dental concrete not only reduces the entrance of water into the joints but also smooths the channel surface that, in turn, will reduce the possibility of turbulent flow, thus keeping overall erosive forces



a. Spillway flow

b. Sectional view

Figure 1. Generalized representation of rock bolting at Serpentine emergency spillway, western Australia (after Gordon 1965)

to a minimum. Dental concrete should be applied as a continuous surface without feathered edges. A minimum thickness of perhaps 20 cm should be considered as being capable of resisting erosion (Table 9).

Table 9

Conditions for Employment of Dental Concrete

Presence of open (approximately 10 mm or more) discontinuities and a significant degree (approximately 15 to 30 cm) of vertical microtopography between high and low areas of the rock surface.
Where discontinuity frequency is excessively high (i.e., of very close spacing; less than 15 to 30 cm), the ability of dental concrete to hold channel-surface blocks to the spillway is probably minimal.
Competent, reasonably strong (> 5 MPa) rock at the channel surface, to create a concrete-rock bond capable of resisting uplift and plucking around relatively thin edges.

Costs of cement-based remediation

65. Costs of implementing concrete-based remediate measures are greatly affected by site-specific conditions. Table 10 gives approximate cost ranges for typical emergency spillway remediation conditions.

Rock bolting

66. Rock reinforcement through rock bolting addresses two general concepts, (1) consolidation of the rock mass or (2) application of sufficient compressive force normal to failure-susceptible discontinuities to overcome tendencies to slide (Figure 1a). Rock bolts represent a method of distributing compressive forces across discontinuity surfaces; either to resist sliding (the most common application) or to bring individual discontinuity-bounded rock-mass blocks closer together, so as to be in tight contact and to offer resistance to uplift. Resistance to uplift, in a rock-bolted rock mass is gained not only by friction between more tightly-contacting rock blocks, but by the fact that discontinuities become largely closed to entry of water, hence reducing the potential for uplift (HQUSACE 1978 and Bennett et al. 1985).

67. Subhorizontal stress relief (exfoliation or sheet jointing) is especially adaptable to rock-bolt retention. Such a case was encountered at Serpentine Dam, near Perth, western Australia. Sheet joints were there

Table 10

Approximate Costs of Cement-Based Remediation Methods

Technique	Cost/Unit
Grouting*	$1.50-150/m^2 ($0.50-50/ft^2)
Lean concrete	
Bulk filler not exposed to erosive forces	$30/m^2
Open-fracture filling	$75-125/m^2
Shotcrete (Gunite)**	Assuming coverage of 10 cm (4 in.) thick
Standard	$20-40/m^2 ($ 2-4/ft^2)
Reinforced	$60-90/m^2 ($7.20/ft^2)
High strength concrete	
Standard (unreinforced)	$70/m^2 ($2-4/ft^2)
Soil cement/rollcrete	
Used as a blanket-type cover over selected (erosion-initiation) points in the emergency spillway channel	$10-25/m^2 ($7-14/ft^2)
Reinforced concrete	
A primary resistance to erosion	$50-110/m^2 ($5-10/ft^2)

Notes: All cost multipliers to convert from earlier years to present were modified from Albritton, Jackson, and Bangert (1984); costs give consideration to the relatively smaller volumes of cement-based remedial methods than are normally applied with cement-based material on construction projects. The costs given above are approximations and are to be used in a relative sense.

* See Albritton et al. 1984.
(1.6 × 1984 dollars = 1987 dollars)

** Sage (1977) (1974 prices × 3 = 1987 prices).

"subparallel to the natural rock surface," herein interpreted to outcrop along one side of the channel and to strike about parallel to the channel axis, and dipping, unfavorably, at 50 deg toward the channel (Gordon 1965). Rock bolting was considered (Figure 1b) as a means of limiting the potential of a block slide of jointed rock into the spillway channel.

68. A large variety of rock-bolt types and anchorage technologies are available. Most of rock-bolt technology deals with the need to reinforce relatively large masses of rock slopes. For emergency spillway applications, in which most of the force-resistance requirements are to reduce or to counter uplift and plucking, rock bolts need only be single-rod varieties of relatively short length and held under only modest compression or by relatively short lengths of borehole cementation (Tables 11 and 12).

Table 11

Conditions for Employment of Rock Bolts

Most effective when the spillway channel or channel walls contain a discontinuity set that dips parallel or subparallel to the wall slope or channel floor.
Least effective when dominant discontinuity set is vertical or when multiple sets are closely spaced (at spacings of less than approximately 60 cm).
Rock masses to be reinforced must be composed of material having a compressive strength > 5 MPa.
For application in relatively small areas of the spillway or channel walls, especially at those areas/locations that appear to be particularly susceptible to erosion or to initiation of erosion.
Commonly utilized in conjunction with grouting, dental concrete, and wire-mesh blankets.

69. Yieldable rock bolts offer a means of resistance to surge-type dynamic, hydraulic forces. Such force might be encountered in downstream portions of some spillway channels subject to heavy debris flow (such as timber and boulders), which could originate in steep forested terrane, especially in weak-rock or tectonically active regions. Yieldable rock bolts can be used to elastically react to dynamic impact from bedload passage similar to shock absorbers.

Table 12

Costs Related to Employment of Rock Bolts

Element	Cost
Drilling	
medium hard rock	$ 9-13/m
hard rock	$12-20/m
Bolt	$ 6-9/m
Installation to include epoxy or grout	$20-30 each

Wire mesh

70. Highly jointed rock masses approach a condition in which the spillway channel is composed essentially of rock blocks. Where weathering is not extensive, it may be adequate to employ only a heavy, rock-bolt-anchored, wire mesh stretched over the channelway. Wire mesh may be plastic-coated to prevent corrosion. A double-twist mesh should be considered as a means of limiting propagation of any local break. The mesh should be anchored by bolt tension less than the tensile strength of the wire. Properly installed mesh should effectively stop the scouring of blocks larger than the mesh openings, essentially retaining the competence of the spillway channel surface.

71. Design considerations for mesh retention are: (a) appropriate mesh-opening size which is smaller than the smallest blocks in the channel, (b) proper anchorage in competent rock, and (c) the use of an upstream debris barrier to eliminate ripping of the mesh by floating and suspended trees and other debris.

72. The use of a mesh-blanketed channel to resist erosion is completely dependent upon mesh continuity and anchorage. Debris, such as uprooted trees, will cause the greatest damage to both mesh and anchorage. Ideally, trees and logs should be cleared from emergency spillway channels. Where this is not possible, an appropriate debris barrier must catch whatever are the typical floating debris of the upstream channel. Where a significant debris-generation potential exists in the watershed, more than one barrier might be required. For example, two or three nets suspended from buoyed cables could be installed as a series. However, under no circumstances should debris barriers impede passage of spillway overflow. Only under special circumstances,

such as water drawn from below the surface of the reservoir, would consideration of bedload debris be necessary.

73. A less common threat of mesh damage stems from rock brought down from spillway channel reaches located upstream from the repaired section. In most cases this rock should not result in ripping and widespread destruction of the wire-mesh blanket. Even if one section of the mesh was damaged by these rocks, it is probable that only a small area would be effected, and repairs would be inexpensive (Tables 13 and 14).

Hydraulic energy dissipators

74. An energy dissipator is a concrete, gabion, or riprap (rock) structure so placed as to reduce the energy of impinging water. Such structures act to reduce flow velocity or to turn the direction of flow without destructive erosion. A variety of sizes and shapes can be used for almost any

Table 13

Conditions for Employment of Wire Mesh

Where sections of the channel floor or sidewall are composed of rock blocks which are too small to employ rock bolting techniques.
Rock blocks must be large enough not to pass through the mesh.
When rock block size varies to a large degree, mesh can be used in conjunction with rock bolts.
Corrosion resistance of wire must be included in design.

Table 14

Costs Related to Wire Mesh

Mesh Size	Cost/Unit
Chain-link type	
6 gage = 4.9mm (0.192 in.)	$13-27/m^2$ (\$1-\$1.25/ft^2)
9 gage = 3.7mm (0.144 in.)	\$6-\$21/m^2 (\$0.60-\$0.84/ft^2)
11 gage = 2.9mm (0.116 in.)	\$4-\$11/m^2 (\$0.40-\$0.60/ft^2)
Triple-twist type	
11 gage = 2.9mm (0.116 in.)	\$12/m^2 (\$0.50/ft^2)

Note: After Sage (1977) (1987 prices = 1975 price × 2.79).

location. Dissipators are constructed from concrete blocks, gabions, riprap, or any other durable material that will effectively dissipate flow energy to force levels small enough to preclude unacceptable erosion.

75. Energy dissipation is dependent upon dissipator size and location in the channel as well as distance from any other dissipators. Design of energy dissipators is based on hydraulic theory and considers such parameters as channel shape, discharge, tailwater elevation, and maximum expected flow velocity.

76. Energy dissipators can effectively reduce the erosive force of any given flow event. They may be effective by themselves in appropriately minimizing the erosion potential, but, at many locations, it may be advisable to use energy dissipators in conjunction with other measures to ensure the competence of the reservoir, retention of the main embankment, and appropriate reduction of downstream impacts (Table 15).

Table 15

Conditions for Employment of Energy Dissipators

Steep channel gradients where turbulent flow is possible.
Provision for a suitable subgrade or anchor for the dissipation structures to ensure their competence.
Appropriate hydraulic conditions particularly with respect to headwater and tailwater elevation(s).
Scale and numeric modelling is appropriate for large projects.

77. Stairstep energy dissipators are formed to slope backward, into the upstream section of a spillway, creating numerous inclined surfaces that dissipate flow energy as the water travels up each surface. In a situation where the emergency spillway is excavated into tightly jointed, competent bedrock, with weak or weathered rock in the channel below the spillway, it may be very beneficial to construct the downstream portion of the spillway structure as a tilted, stairstep structure. This would reduce the energy of the water at the toe of the spillway and thus reduce the erosion by the flow downstream.

78. This option could also be considered in cases where the emergency spillway channel has a very steep outlet slope.

79. Costs related to energy dissipation will vary depending upon materials used (onsite, as compared with man-made or brought in), site conditions (geologic materials and discontinuities present), what type of anchoring must be applied, and location. Due to these factors no costs have been quoted, however the cost of properly designed energy dissipators would be less than most types of cement-based channel linings.

Gabions

80. Gabions, an outgrowth of an ancient military engineering technique, may be used as liners for channels subjected to erosion. When used as channel lining, they may require a proper filter bed as a measure to stop channel-type undercutting (especially on gradients in excess of 5 percent, 1:20 V:H). The latter situation prevails if the velocity beneath the gabion is great enough to remove the subgrade material. The velocity felt by the subgrade material will depend upon the hydraulic setting as well as the gabion thickness. There have been situations where the use of a geotextile as a filter blanket material has resulted in pore-pressure problems*. For designs against high-velocity flow, a sufficient thickness of filter bedding should be placed between the surface of the channel and the gabions to provide relief of uplift pressures without removal of the natural ground (Copeland 1980). Gabions and Reno Mattresses (essentially, a gabion that is mattress-shaped instead of boxshaped) require a rock-fill material of less than one-half the diameter required for riprapped channel surfaces (Agostini and Cesario 1984).

81. Heavy bedload transport of hard, angular particles, such as chert, can eventually cut or shear the basket wire. However, such failure is not a problem at most emergency spillways due to the fact that all water entering the channel will usually flow from the top of the reservoir and, thus, be without bedload except as scoured from upper reaches of the emergency spillway channel itself. Also, the wire must withstand corrosion and is usually plastic coated.

82. Gabions have been observed to withstand velocities up to 8 mps (25 fps) on 33 percent (1:3) slopes if the gabion layer is at least 45 cm (18 in.) thick. Normally, gabions lining channels will not require anchorage, because they are wired together and the weight of the combined

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* Personal Communication, 1987, A. Crowhurst, Technical Director, Macciferri Gabions, Inc.

units is great enough to provide stability against flow. In situations where additional anchorage is required, the gabions can be partially buried below subgrade, providing additional flow resistance. A recommended gabion design* in order of installation is, geotextiles, basal sand/gravel bedding filter, then gabions. In most cases, a sand/gravel bedding filter or geotextile blanket will be sufficient to protect the gabion subgrade material from being scoured**. Where the interface velocity is expected to be high, such as along a steep channel or from oblique flow directions, an open-work gravel filter of sufficient thickness is recommended to dissipate energy at the gabion/ substrate interface (Simons, Chen, and Swenson 1984). For channel gradients greater than 5 percent (1:20), gabion blanket installation can be considered as an energy dissipation mechanism to reduce flow velocity.

83. Gabions can be more cost-effective than riprap whenever the required gabion liner thickness is less than what is needed for riprap. "Overall thickness of gabions can typically be one-half to one-third that of riprap protection."** Research at Colorado State University revealed that gabion or Reno Mattress fill rock of a specific diameter can withstand greater flow velocities than riprap of the same diameter (Simons, Chen, and Swenson 1984) (Figures 2 and 3).

84. Another model study found that gabions oriented with their longitudinal (long) axes parallel to the flow were more effective than those oriented perpendicular to the flow (Copeland 1980). However, when gabions or Reno Mattresses are tied together, gabion orientation does not appear important on the basis that "The strength of the wiring between adjacent gabions if properly installed is greater than that of the mesh itself."**

85. Size range of infilling stone selected must be uniform, although sufficiently large so as not to pass through the wire mesh (Copeland 1980).

86. Reno Mattresses are a modern (since the early 1960's) innovation of the "box gabion" (Agostini and Cesario 1984) in which the basket is made considerably wider and longer than its thickness (height), as a flat parallelepiped. This monolithic blanket, or mattress-effect resists displacement by high-velocity flow (Simons, Chen, and Swenson 1984). During high-velocity

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* Personal Communication, 1986 (Dec), Mel Schaefer, Consulting Hydrologist, Spokane, Washington.

** Personal Communication, 1987, A. Crowhurst, Technical Director, Macciferri Gabions, Inc.

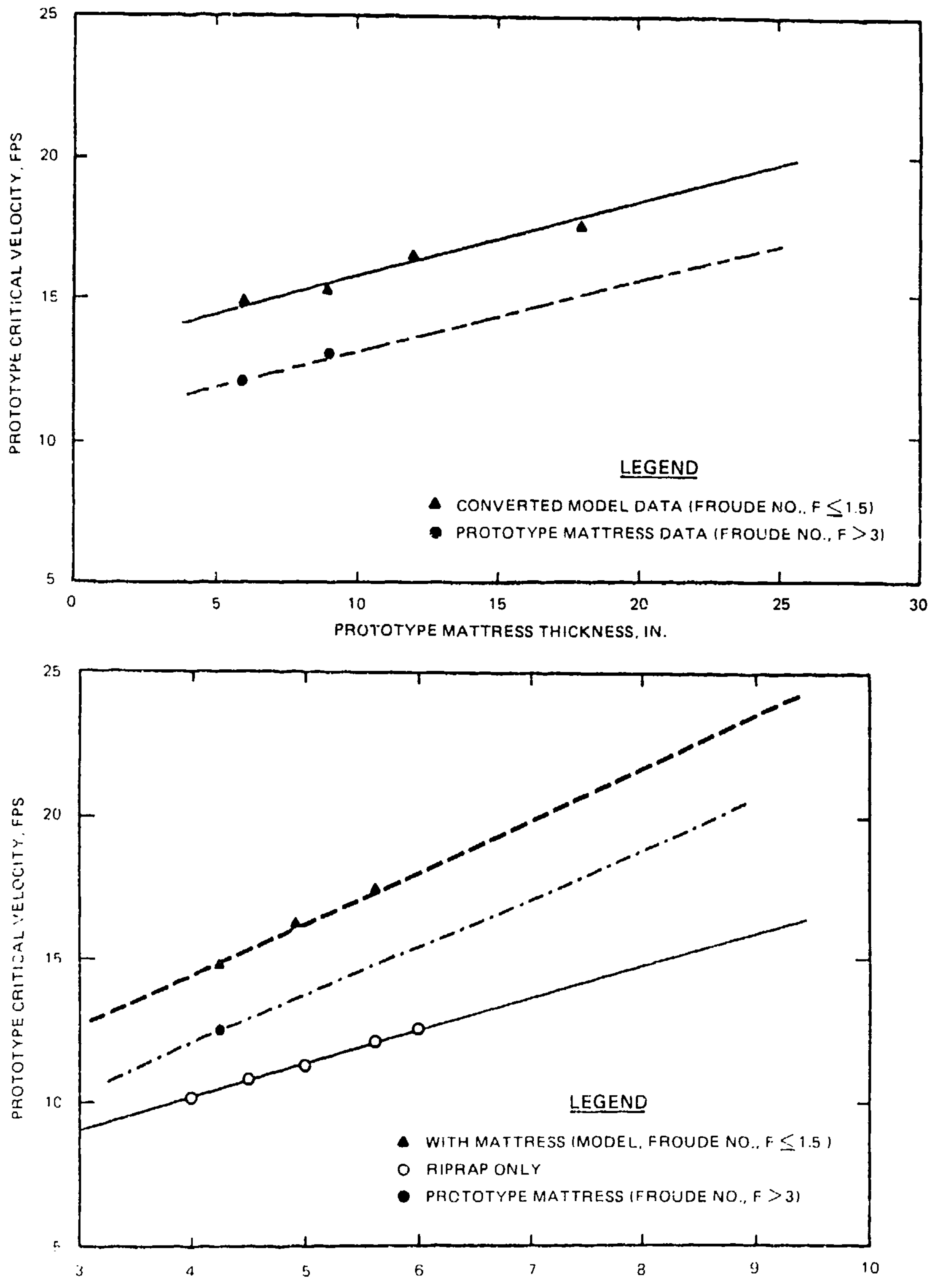

Figure 2. Critical velocity that initiates rock movement as a function of mattress thickness (Simons, Chen, and Swenson 1984)

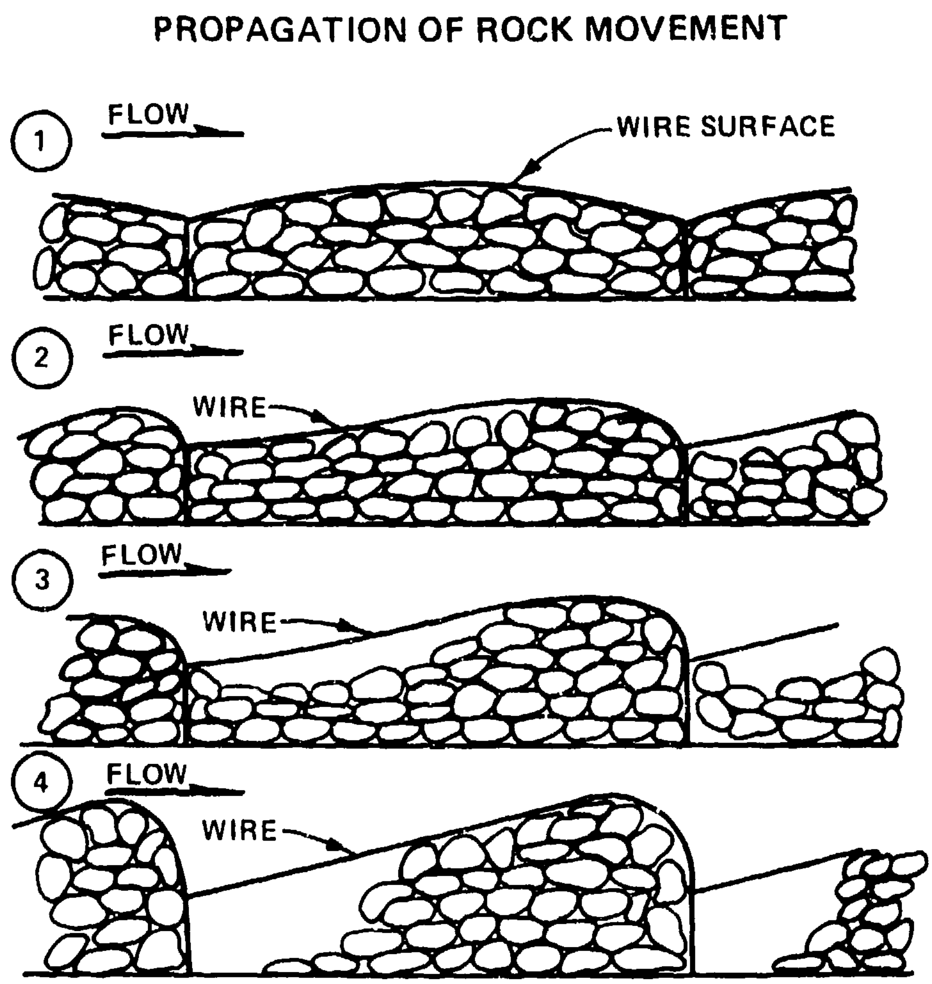

Figure 3. General pattern of rock movement within a Reno Mattress-type gabion as velocity is increased 1-4 (Simons, Chen, and Swenson 1984)

flow, the rock filling tends to migrate downstream and bunch-up within individual, large baskets (Figure 3). Such migration can be minimized by placement of vertical wire baffles to divide the mattress into cells (Figure 3). Migration of rock infilling does not appear to reduce mattress effectiveness unless portions of the underlying channel surface become exposed. Once in-basket rock movement occurs, an equilibrium state is reached for each particular flow velocity.

87. Reno Mattresses can be strengthened and made flexible, yet non-deforming, by injection with sand/asphalt mastic. A mix ratio of 66-73 percent by weight sand, 12-16 percent filler, and 15-18 percent bitumen is recommended by Agostini and Cesario (1984). Such mastic stabilization can be partial or can be extended through the entire thickness of the mattress to provide not only an impermeable structure but a variable degree of flexibility as well. Mastic-grouted Reno Mattresses can accommodate relatively large settlements and deflections wherever the underlying soil is threatened by erosion. Mastic grouting can also be used to create a relatively smooth upper or side flow surface in which bedload abrasion is reduced significantly because there are fewer microdepressions and other indentations offering points of attack. The inherent lining flexibility is equally attractive in areas of high seismicity.

88. Reno Mattresses can serve as spillway armoring, especially when injected with mastic. Such a lining has advantages at emergency spillway channels excavated into coarse, erodible, unconsolidated materials, incapable of supporting a vegetated surface or where anticipated flows would create rapid erosion. Sand/asphalt mastic may be susceptible to abrasion and would require a formulation to resist that erosive mechanism.

89. Critical velocities as well as the limit velocities, as shown in Table 16, are for sustained flow and are dependent upon the spacing of the baffle within the gabion or Reno Mattresses. If the baffle spacing is reduced to about one-half that used in the standard gabion (Reno Mattress), then the limit velocities can be expected to increase by about 25 percent* (Table 17).

90. Due to the fact that a flow event in an emergency spillway is usually of short duration (days or weeks at most), the limit velocity should be considered for design purposes in reducing erosion at emergency spillways. A minor amount of repair following a flow event should be anticipated when using the limiting velocities. However, such flow events are usually rare, and the amount of repair relatively minor (i.e., rearrangement of the rockfill, and some gabion basket cover lid repairs) such that cost savings will occur.

91. Costs for gabions and Reno Mattresses are presented in Table 18 and do not include delivery and installation charges; these costs can be expected to go up only a few percent each year.* The largest variable for gabion

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* Crowhurst, op. cit.

Table 16

Thickness Requirements of Gabions and Reno Mattresses as a Function of Average Flow Velocity (Channel Revetment Use) (after Agostini and Cesario 1984)

Type	Thickness m	Rockfill Size mm	Rockfill d_{50} m	Critical Velocity m/sec	Limiting Velocity m/sec
Reno Mattresses	0.15-0.17	70-100	0.085	3.5	4.2
		70-150	0.110	4.2	4.5
	0.23-0.254	70-100	0.085	3.6	5.5
		70-150	0.120	4.5	6.1
	0.30	70-120	0.100	4.2	5.5
		100-150	0.125	5.0	6.4
Gabion	0.50	100-200	0.150	5.8	7.6
		120-250	0.190	6.4	8.0

Note: Critical velocity corresponds to the conditions of initial motion displacement of rockfill; limiting velocity is the threshold where small deformation of the Reno Mattress occurs due to rockfill displacement.

Table 17

Conditions for Employment of Gabions

Can be used as a primary channel lining material and for cutoff walls.

Due to relatively high cost, should only be used for portions of the channel and not as a complete lining.

Most cost-effective when rock to fill baskets is available at or near the site.

Must always consider the subgrade material to ensure competence of the portion of the channel where gabions have been installed.

Should not be used if loose stone are expected to be transported in the flows over the gabions due to cutting and abrasion of the gabion wire (even PVC coated).

The use of gabions in salt water or highly acid soil or other wire-eroding chemicals should be avoided.

Table 18

Costs for Gabions/Reno Mattresses*

Item	Weight	Price, $
	Gabions	
GE 6 by 3 by 3	39.65	34.10
GE 9 by 3 by 3	56.61	48.90
GE 12 by 3 by 3	71.48	61.50
GE 6 by 3 by 1.5	27.30	23.50
GE 9 by 3 by 1.5	39.28	33.00
GE 12 by 3 by 1.5	49.33	42.00
GE 6 by 3 by 1	23.84	20.70
GE 9 by 3 by 1	34.41	28.90
GE 12 by 3 by 1	43.30	36.00
GM 2 by 1 by 1	46.29	42.10
GM 3 by 1 by 1	65.09	59.60
GM 4 by 1 by 1	83.51	76.80
GM 2 by 1 by 0.5	33.22	29.40
GM 3 by 1 by 0.5	46.61	42.00
GM 4 by 1 by 0.5	60.31	53.10
GM 2 by 1 by 0.3	26.80	23.80
GM 3 by 1 by 0.3	38.09	33.40
GM 4 by 1 by 0.3	49.08	43.00
GE 18 by 6 lid	40.54	30.00
GE 18 by 6 by 1 base	74.87	61.80
PE 6 by 3 by 3	37.15	43.10
PE 9 by 3 by 3	53.23	61.70
PE 12 by 3 by 3	67.25	79.30
PE 6 by 3 by 1.5	25.57	29.00
PE 9 by 3 by 1.5	36.61	42.20
PE 12 by 3 by 1.5	46.28	55.30
PE 6 by 3 by 1	21.91	25.50
PE 9 by 3 by 1	31.82	38.60
PE 12 by 3 by 1	40.94	47.20
PM 2 by 1 by 1	44.08	56.60
PM 3 by 1 by 1	62.38	76.80
PM 4 by 1 by 1	78.99	99.10
PM 2 by 1 by 0.5	29.82	37.90
PM 3 by 1 by 0.5	43.83	54.60
PM 4 by 1 by 0.5	56.06	70.40

(Continued)

Notes: PE = PVC coated and English units.
GE = Galvanized and English units.
PM = PVC coated and metric units.
GM = Galvanized and metric units.
All lacing wire included with prices listed.
All weights are in pounds.
* Crowhurst, op. cit.

Table 18 (Concluded)

Item	Weight	Price, $
	Gabions (Continued)	
PM 2 by 1 by 0.3	25.42	31.50
PM 3 by 1 by 0.3	35.12	44.40
PM 4 by 1 by 0.3	46.14	56.80
PE 12 by 3 by 1 base	28.01	26.68
	Reno Mattresses	
GE 9 by 6 by 6 base	22.38	23.60
GE 12 by 6 by 6 base	28.37	27.00
GE 9 by 6 by 9 base	24.04	27.80
PE 9 by 6 lid	14.26	13.10
GE 12 by 6 by 9 base	30.98	35.50
GE 12 by 6 lid	18.27	16.20
PE 9 by 6 by 6 base	28.58	36.80
PE 12 by 6 by 6 base	37.09	40.50
PE 9 by 6 by 9 base	28.63	44.50
PE 9 by 6 lid	17.51	21.70
PE 12 by 6 by 9 base	37.45	57.50
PE 12 by 6 lid	22.71	28.30
PE 40 by 6 lid	71.30	100.00
PE 40 by 6 by 9 base	120.15	185.60

installations is labor cost. Average man-hours for gabion/Reno Mattress installation done by hand are:

a. 2-4 man-hours/cubic yard for gabions.

b. 0.5-1.25 man-hours/square yard for Reno Mattresses.

If portions of the gabion installation are mechanized, the final cost ends up being about the same.* Presently, a good grade of short-haul (< 7 km) Midwest aggregate, for example, runs about $15/ton (1 cu yd = 1.5 tons). With all costs taken into account, the average installed cost in Missouri is about $80/cu yd.**

Cutoff wall

92. This technique places a vertical wall-barrier, installed to an appropriate depth, at the top of the emergency spillway and/or at other locations along the channel.† Cutoff walls can be designed in a variety of types and can be constructed of a number of materials. Such materials include concrete, sheet piles, logs, gabions, etc. (Table 19).

Table 19

Conditions for Employment of a Cutoff Wall

Situations where there is a high probability of headward cutting taking place during a flow event.
Effective when site conditions allow the wall to be keyed into a competent rock unit with minimal erosion potential.
Most effective when used as a series of walls.
Most suitable in weak rock with closely spaced discontinuities.

93. One example of a cutoff wall being considered is at the Sam Rayburn Dam, east Texas, which embodies "the construction of a deep drilled pier cutoff wall along the alignment of the existing spillway weir" supplemented by a "series of three additional cascade walls across the spillway discharge channel" (Cameron et al. 1986). The measure would be designed to "prevent total failure of the spillway," but "extensive repairs would be required after

* Crowhurst, op. cit.
** Personal Communication, 1987, R. Russo, Maccaferi Gabions, Inc., St. Louis, Missouri.
† Schaefer, op. cit.

the passage of any significant spillway discharge. This system has an estimated cost of $50 million" (Cameron et al. 1986).

94. Costs related to employment of cutoff walls will vary depending on the type of material and site depth conditions. The costs quoted here are only for concrete walls (Table 20).

Table 20

Costs Related to Concrete Cutoff Walls

Technique	Assumption	Cost/unit
Excavated in the dry, shored/formed	Reinforced concrete, less than 10 ft deep	\$20 to 40/ft^2 of surface area (one side)
Excavated in the wet, pumped, shored/formed	Reinforced concrete, less than 10 ft deep	\$25 to 50/ft^2
Excavated in weak rock, dry, unshored/unformed	Reinforced concrete, less than 10 ft deep	\$30 to 70/ft^2

Removal of woody vegetation

95. Woody vegetation and fallen (or toppled) trees can cause turbulent flow concentration, which, in turn, increases the erosive forces or can actually cause a logjam in the spillway channel. At the Grenada Dam in Mississippi, one flow event caused channel widening which toppled a large number of trees into the channel. A recommendation was made to remove these trees to avoid the possibility of a logjam. Bodies of woody vegetation are also known to increase the probability of damage through flow concentration, which increases the velocity and flow rate in portions of the channel which are adjacent to the vegetation. Vegetation removal was recommended at Little Youghiogheny Dam No. 1, Maryland, during the National Dam Inspection Program (Ackenheil and Associates 1979). Removal of woody vegetation would be far less expensive than the possible damage that such vegetation could cause during flooding (Table 21).

96. Costs related to vegetation removal will vary considerably. The two end members of this cost range are the minimal outlay required for rough mowing or herbicide treatment in an arid environment to the significant costs related to grubbing-removal of small, rooted trees in a humid climate (Table 22).

Table 21

Conditions Requiring Removal of Vegetation

When trees or shrubs of any kind are present on the floor of the emergency spillway channel.
Most effectively employed as a preventive measure; i.e., removing trees and shrubs as they begin to grow, either by hand or with an herbicide (in this case the use of an herbicide may be less expensive).

Table 22

Costs Related to Removal of Woody Vegetation

Technique	Assumption	Cost/unit
Rough mowing, dry climate	Denial of substantial growth of woody vegetation (per 12 months)	\$125-175/hectare \$ 50- 70/acre
Rough mowing, humid climate	Denial of substantial growth of woody vegetation (per 3 months)	\$500-650/hectare \$200-265/acre
Herbicide, humid climate	Initial kill of substantial growth	\$ 90-100/hectare \$ 35-110/acre
Spot cutting, dry climate	Removal of substantial growth of woody vegetation, plus removal of cuttings (2-person crew)	\$185-285/hectare \$ 75-110/acre
Spot cutting, humid climate	Removal of substantial growth of woody vegetation, plus removal of cuttings (2-person crew)	\$370-560/hectare \$150-225/acre

Removal of erosional outliers

97. Erosional outliers are defined herein as any structure or naturally occurring feature that has the tendency to concentrate flow and, therefore, increase the erosive force in a specific section of the emergency spillway channel. Such features include access roads, fences, boulders, a fault scarp or similar feature, or a stand of trees, etc. The presence of these types of features can cause specific sections of an otherwise erosion-resistant channel to be severely damaged. In the worst case such damage can spread during the flow event and create a breach, through the spillway, or in some very severe cases, through the main embankment, causing failure.

98. Removal of such features, in many cases will be relatively inexpensive. However, in situations where an access road crosses the spillway, appropriate modifications may require large sums of money along with creative engineering. Following the erosion assessment, a decision will need to be made at each location as to the cost effectiveness of removing or modifying all of the erosional outliers to address the problems of safety and financial considerations that will be incurred in the event of flow. At many locations it may be more effective to combine removal or modification with another measure to provide adequate channel protection (Table 23).

Table 23

Conditions for Removing Erosional Outliers

Any site condition that will interrupt flow should be considered for removal.

99. No costs are quoted herein for the removal of erosional outliers. This is due to the fact that the types of outliers are quite variable, and the cost of removal is totally dependent on the type. For example, the cost of rerouting an access road will be quite different from the cost of grading or removing a fault scarp.

Riprap

100. During one model study regarding the design of a rock-fill dam (Shannon and Wilson 1961), it was found that the greatest protection against erosion occurred if the rocks are placed in two layers with the rocks in the bottom layer raked to grade, and the top layer placed with the thin dimension vertical and the long dimension parallel to flow. Additionally, all of the upper-layer stones were placed so that they were wedged against the downstream rock. By placing rock in this manner, it was found that only the first row of rock would be disturbed during flow, and "when any one rock was displaced at all, it was immediately swept downstream from the model" (Shannon and Wilson 1961) without disturbing any of the other rock. The conclusion of this study is "that properly placed tabular rock with a long dimension noticeably greater than its average minimum dimension is stable with the following slopes and average riprap thickness dimensions":

1:6 slope = 0.5 m

1:5.5 slope = 0.66 m

1:5 slope = 0.77 m

101. When designing a riprapped emergency spillway surface, it is important to determine the equivalent thickness of sufficiently large rock to resist the tractive force of the design discharge. Depending on the gradient and expected flow velocities, it may be necessary to use some type of filter material to dissipate pore pressures and provide stability. Guidance for the design of riprap protection is given in Shannon and Wilson (1960, 1961) and HQUSACE (1970) (Table 24).

Table 24

Conditions for Employment of Riprap

Most cost-effective when rock can be obtained on or near the site.
Most appropriate where near-horizontal channel slopes exist.
When used over clays and/or silts and when high velocities are expected an appropriate filter should be considered.

102. Lower Chapman Dam, Oregon, which is owned and operated by the Star Mountain Ranch (US Bureau of Land Management 1983), has a total capacity of 1,460 acre-ft, and is used for irrigation and flood control (US Soil Conservation Services 1982). The dam is 32 m (105 ft) high, and the emergency spillway was designed according to the "100 year exceedence interval to 1/2 PMF" (US Soil Conservation Services 1982). The 100 year PMF at this dam was calculated to be 1,835 cfs. A large-flow event of February 1982 removed several thousand cubic metres of material from the emergency spillway constructed in an unconsolidated cobble, boulder, and sand alluvium (US Soil Conservation Services 1982). Over this alluvium was placed 60-cm (2-ft) armour of angular cobble and boulder-size basalt riprap (US Soil Conservation Services 1982). All of the riprap was stripped by the 1982 flood event (US Bureau of Land Management 1983), and vertical erosion channels of 7 to 8 m (20 to 25 ft) were created (US Soil Conservation Services 1982).

103. The prime remedial measure recommended was to compact onsite fill to a 1:2 slope, overlaid with 2.6 m (5 ft) of riprap, held in place by a welded mesh of No. 5 rebar, and secured by concrete cutoff trenches upstream

and downstream. The estimated cost of the treatment was $90,000 (US Soil Conservation Services 1982). Dimensions of the emergency spillway were not included in the report; therefore, unit costs could not be determined (Table 25).

Table 25

Costs Related to Riprap

Stone riprap; excavated from dedicated quarry producing select rock	$\$20\text{-}50/yd^3$

104. The recommended measures were not carried out by the owner, and a flood the following March brought about a spillway failure which released about 1,000 acre-ft of water from reservoir storage, following about 2 cm (0.75 in.) of rain over the previous 24 hr (US Bureau of Land Management 1983).

Relief of uplift pressure

105. Otherwise, intact rock masses bound by widely spaced discontinuities (spaced at more than 1.0 m) are subject to hydrostatic uplift pressures especially during flooding. Where these massive blocks are bound by a regular network of open joints (such as at Black Butte Dam, California), uplift pressures may be naturally relieved through the joint boundaries.

106. Measures to relieve uplift pressures should be considered at those sites treated by closure of bounding joints, such as by grouting or a combination of grouting and rock bolting. A simplistic method of relieving uplift pressure would be to place one or more centrally located, vertical boreholes into each distinct joint block and terminate at some depth (say 30 to 60 cm) below the most distinct lateral (horizontal) bounding discontinuity. Such near-horizontal discontinuities can often be detected by manual probing with a hooked stiff wire. Uplift pressure-relief boreholes should be relatively small (70- to 100-mm diam) and backfilled with small-diameter granular material, graded to act as a barrier to sedimentation plugging of the relief hole yet porous enough to allow for pressure relief* (Tables 26 and 27).

* Personal communication, 1986 (Oct), J. H. May, US Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Table 26

Conditions for Employing Relief of Uplift Pressures

Any situation where large rock blocks are present, and the potential exists for those blocks to be fragmented by uplift pressures during flow, thus being susceptible to plucking.
Rock blocks must be unweathered to a depth of less than 1 cm from surface.

Table 27

Costs Related to Relief of Uplift Pressures

Technique	Requirements	Costs
Pressure relief boreholes	70- to 100-mm diam, ~5-ft-deep (minimum) Tri-cone bit	$900/day for drilling rig, 25 holes/day, $8 to $11/ft

Grass lining

107. Ordinarily, there would be little need or applicability for the use of vegetation in excavated spillways in hard indurated rocks, however, vegetation may be helpful in spillways cut in softer rocks and in the outlet channels. Selection of natural grasses for channel lining must be made on the basis of climatic and soil characteristics. The grass must be chosen either to provide stability as a function of projected flow velocity or on the basis of discharge channel gradient. Bunch grasses, such as lespedeza, alfalfa, and kudzu, can develop localized flow channels and are therefore unsatisfactory for lining (Chow 1959). For gradients greater than 5 percent fine, uniformly distributed sod-forming grasses (e.g., Kentucky bluegrass, Bermuda grass, and smooth brome) are recommended. Fast establishing Bermuda grass, weeping love grass, or annuals should be used for temporary protection until native or other grasses are established (Chow 1959). Chow also recommends that bunch grasses be used to reduce silting. Grasses, in general, require semicohesive soils as a rooting medium and 20-25 cm (8-10 in.) of precipitation per year for sustenance.*

* Schaefer, op. cit.

108. Grass linings serve to "consolidate the soil mass of the channel perimeter," and to retard bedload movement along the channel surface (French 1985). However, grass-lined channels cannot generally withstand prolonged inundation and wetness, and they may lose vitality during seasonal dry periods (French 1985). Maximum tolerable velocities for various grasses are given in Table 28; conditions of employment are in Table 29; and costs are in Table 30.

109. Selection of grass species for channel lining should consider the following factors:

- a. Spare vegetal cover should be exposed to velocities less than 3 ft/sec (0.91 m/sec).
- b. Seeded vegetation can generally withstand velocities in the range of 3 to 4 ft/sec (0.91 to 1.2 m/sec).
- c. Quickly developed dense sod is generally resistant to velocities of 4 to 5 ft/sec (1.2 to 1.5 m/sec).

110. Additional flow resistance is gained by deep-rooted, long-stemmed grass, such as fescues which lay over in flow. Such grasses can protect slopes of 5 to 6 percent, with flow velocities as high as 8 to 9 ft/sec.*

111. When a grass lining is planned, consideration needs to be given to the maintenance of the grass. The upkeep will not be as extensive as that of maintaining a lawn. However, occasional repairs will be necessary to keep a good continuous cover, and "volunteers" (trees and bushes) will require removal on an on-going basis.

112. It should be stressed that in case history after case history the velocities experienced in spillway channels are much greater than those that natural grasses can withstand, and, therefore, natural grasses should only be considered in those special situations where the expected velocity is within the range discussed above.

Geotechnical grass

113. The Construction Industry Research and Information Association (CIRIA), of the United Kingdom, is in the process of performing tests on grasses for spillway linings that are reinforced with geotextiles and concrete lattices (Birchall and Pinyan 1986). Thus far, CIRIA has had great success with both the concrete lattice and geotextile systems. The concrete lattice systems perform the best when used in conjunction with a geotextile. This combination proved to be very erosion resistant; however, it is somewhat

* Schaefer, op. cit.

Table 28

Maximum Velocities for Grassed Channel Grade

(after French 1985)

Cover	Maximum Tolerable Velocity*		
	Gradient Range** percent	Erosion-Resistant Soils, ft/sec	Easily Eroded Soils, ft/sec
Fescue	5-6	8-9	5
Bermuda grass†	0-5	8	6
	5-10	7	5
	10	6	4
Bahia			
Buffalo grass			
Kentucky blue	0-5	7	5
Smooth brome	5-10	6	4
Blue gramma‡	10	5	3
Tall fescue			
Grass mixtures	0-5	5	4
Reed canary	5-10	4	3
Lespedeza servicea	--	--	--
Weeping love grass	--	--	--
Yellow bluestem	--	--	--
Redtop††	0-5	3.5	2.5
Alfalfa	--	--	--
Red fescue	--	--	--
Common lespedeza†,	--	--	--
Sudan grass†	0-5	3.5	2.5

* Specify velocities exceeding 1 m/sec (5 ft/sec) only where good covers and proper maintenance can be obtained.

** Specify for slopes less than 10 percent except for vegetated side slopes in combination with a stone, concrete, or highly resistant vegetative center section.

† These annuals should be used on mild slopes (less than or equal to 5 percent) or as temporary protection until permanent covers are established.

†† Specify for slopes less than 5 percent except for vegetated side slopes in combination with a stone, concrete, or highly resistant vegetative center section.

‡ Use on slopes steeper than 5 percent is not recommended.

Table 29

Conditions for Employment of Grass Lining

Sufficient annual precipitation and appropriate temperatures.

Expected velocities are low enough to allow grass to provide desired level of protection.

Table 30

Costs Related to Grass Lining

Components	Costs
Topsoil	\$ 20/yd^3
Seeding	\$ 940/acre
Sodding	\$ 5/yd^2
Fertilizer (no insecticides)	\$ 710/acre
Maintenance	
mowing	\$ 100/acre/yr
refertilization	\$ 270/acre/yr
weeding/pruning	\$2,000/acre/yr

Note: Costs taken from US Environmental Protection Agency (1985) and adjusted for inflation.

Table 31

Conditions for Employment of Geotechnical Grass

Most appropriate in areas where climate is suitable for grass lining, but expected velocities are greater than standard grass linings can withstand.

Appropriate for spillways in soil and soft rock.

Appropriate where aesthetics are important.

Table 32

Costs Related to Geotechnical Grass

Components	Costs
Topsoil	$ 20/yd^3
Seeding	$ 940/acre
Sodding	$ 5/yd^2
Fertilizer (no insecticides)	$ 716/acre
Maintenance	
mowing	$ 100/acre/yr
refertilization	$ 270/acre/yr
weeding/pruning	$2,000/acre/yr
Geotextile	$ 0.70/ft^2

Note: Costs taken from US Environmental Protection Agency (1985) and increased by 5 percent per year for inflation.

114. The most surprising portion of the CIRIA study was the performance of grass linings that were only reinforced with a geotextile to strengthen the root system. Geotextiles used in these tests were a three-dimensional nylon mat and a two-dimensional polyethylene mat. Both geotextiles performed in such a way as to show that design velocities could be in the range of 14.8 to 18 ft/sec. Compared with the concrete mesh, the geotextiles are approximately $0.70/sq ft. By comparing the CIRIA velocities with those in the previous part, it can be seen that the geotextile actually doubles erosion resistance of the grass with respect to velocity.

Flow rerouting

115. Flow rerouting can be achieved by a number of devices. At Sam Rayburn Dam in east Texas, a new ogee weir, which would raise the level of the emergency spillway crest, was considered as a preventive measure by the US Army Engineer District, Fort Worth. Also, eight 40- by 33-ft tainter gates, located in the main dam, would divert the flood discharge from the emergency spillway and route it to the main channel of the Angelina River. This measure would cost approximately $58 million (Cameron et al. 1986).

116. In situations where the emergency spillway is quite large, located in highly erodible alluvial or residual deposits, and no type of lining is feasible, consideration can be given to rerouting the flow. One possible

condition that might call for such a measure is when the emergency spillway is actually being used as farmland (not a recommended practice) and, therefore, is very erosive and not feasible for lining.

117. It should be remembered that this option only reduces the possibility of flow going over the emergency spillway and does not improve the emergency spillway channel in any way. In most situations, this option will also be very expensive and, therefore, should only be considered as a last resort, after all other options have been considered. When considering this option, it would be important to evaluate the entire reservoir area for another possible location of the emergency spillway. There may be situations where relocation of the emergency spillway would be less expensive than adding a new service spillway (Table 33).

Table 33

Conditions for Employment of Flow Rerouting

Considered only as a last resort when there are no other options for remediation.

118. Costs related to flow rerouting will be greatly variable depending on what is to be done. Such costs will be related to the materials and constructions costs incurred during the raising of an emergency spillway weir, and/or the construction of additional service spillways, and/or the construction (relocation) of a new (or additional) emergency spillway.

Compaction

119. Emergency spillway channels excavated into unconsolidated alluvial or residual deposits are especially susceptible to erosion, especially when the fine-grained materials are low in cohesion. Compaction may be very helpful in reducing erodibility. Creating a more cohesive mass will in turn reduce the erodibility. Compaction densification of the uppermost 6-12 in. of the flow surface will reduce the erodibility. Compaction relative densities of less than 90 percent are generally sufficient for this purpose. The erosion resistance of some spillway channels can often be increased to an appropriate degree by compaction only. Compaction is especially effective when the combined silt and clay fraction is greater than about 25 percent. Among poorly consolidated soils, loess deposits are generally too silt-rich to yield

an increase in their erosion resistance. Recompaction may be required after significant flood events and after freeze-thaw cycles.

120. Compaction is particularly effective when used in conjunction with other measures. For example, subgrade compaction below a topsoil grass-lining layer will provide enhanced protection against erosion in the event that a section of the grass fails. Concrete or gabion-type linings often require compaction of unconsolidated subgrade to protect against settlement (Tables 34 and 35).

121. Compaction can be carried out with a standard roller. A southern California (Gutschick 1985) canal, constructed in montmorillonitic clay soil, has exhibited considerable erosion resistance after being mixed with quicklime and being compacted with a sheeps-foot roller. Mixing with quicklime tended to have a pozzolanic effect on the clay soil. Other than being mixed with

Table 34

Conditions for Employment of Compaction

When the spillway is bedded in sufficient thickness (≥ 1 ft) of unconsolidated material.
Especially when this material has cohesion; e.g., is of silt or clay particle size.
In climates in which grass linings are not possible because of other factors.

Table 35

Costs Related to Compaction

Conditions	Cost
Tilled, moisture-controlled, two 6-in. lifts, onsite material	$\$1-2/yd^2$
Onsite, hauled, mixed, moisture-controlled, two 6-in. lifts	$\$1.50-3/yd^2$
Onsite, moisture-controlled, mixed in place, additive soil or mineral, two 6-in. lifts	$\$2-4/yd^2$
Onsite, hauled, moisture-controlled, mixed adjacent to spillway, additive soil or mineral, two 8-in. lifts	$\$2.50-5/yd^2$

lime and being compacted, the canal is unprotected. Very little erosion has occurred after 12 years of service, including service under one peak flow of 5,300 cfs (Gutschick 1985). This is evidenced by the fact that 12-year old canal grader marks were still visible on the surface.

Multiple use options

122. There are certain conditions in which the location of the spillway makes it possible to use the spillway for more than one purpose. In these situations the uses will compliment each other. One example of such a use is constructing a parking lot in the emergency spillway channel. There may also be other possibilities.

123. At some locations, dams have been constructed in urban areas or recreational park areas. In these situations, if the spillway is conveniently located and it is presently unlined, one possible option would be to construct a parking lot in the channel. To be effective in creating an erosion-resistant channel, the parking lot in such cases would have to be concrete or asphalt paved instead of gravel and oil. This option has been used in a number of emergency spillways located in the US Army Engineer Division, Ohio River* (Table 36).

Table 36

Conditions for Employing Multiple Use Options

Appropriate when spillway is located near populated areas or located in park areas.

Any situation where a second use will reduce the erodibility of the spillway and continue to address safety and proper reservoir use.

Costs Related to Multiple Use Options

Gravel (compacted, 12 in.)	$9/yd^2 (US Environmental Protection Agency 1985)
Asphaltic concrete, 6 in.	Variable
Asphaltic concrete, 6 in., with 8-in. pressure relief gravel base course	Variable

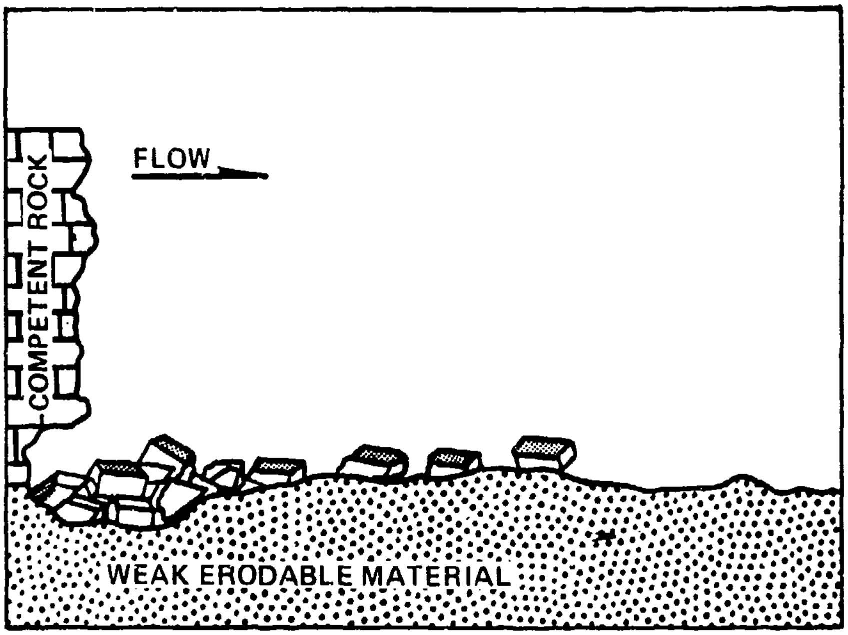
* Personal Communication, 1987, C. P. Cameron, University of Southern Mississippi, Hattiesburg, Mississippi.

Modified ogee weir (ski-jump structure)

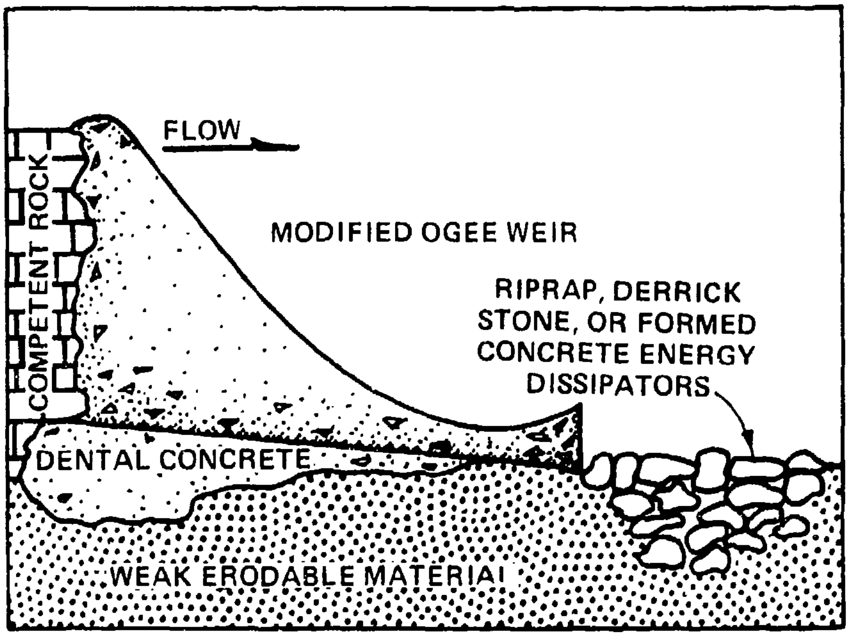
124. In situations where the outlet slope on the emergency spillway channel is steep (approaching a small cliff), a ski-jump structure can be installed at the top of this knickpoint. Hydraulic structures of this type will cause the water to shoot out away from the base of the cliff and reduce the possibility of undercutting. Such structures are n' : only less expensive than a complete channel lining but in some situations are more effective in that they substantially arrest the process of headcutting.

125. Structures of this type can be used in situations where the channel is lined with a competent, relatively erosion-resistant geologic unit that extends to the point of the cliff-like outlet slope. This would be particularly important if the competent unit is not as thick as the height of the cliff (see Figure 4) (Tables 37 and 38).

126. Concrete baffles were used to repair the spillway at the Kerrville State Hospital Dam, Texas. At this location, three reinforced concrete baffles were placed across the spillway to retard the movement of riprap that had been used to bring the spillway to hydraulic grade. The baffles used were 9 in. by 5 ft by 100 ft, with 4-in.-diam drains placed 1.5 ft below the top of the baffle placed at 10-ft centers. During 1978, a flow of 3,200 cfs (90.6 cm/sec) was accommodated by the baffles with only a minor amount of acceptable riprap displacement (Tables 39 and 40).



a. Spillway channel before remediation



b. Spillway channel after remediation

Figure 4. Use of a modified ogee weir as a remedial or preventive measure

Table 37

Conditions for Employing Modified Ogee Weir

Any situation where the potential for undercutting is high, i.e., a very steep outlet slope.

Especially appropriate at steep discharge slopes with very erodible underlying geologic material.

Table 38

Costs Related to Modified Ogee Weir

Components		Cost
Scaling of loose, jointed, and/or bedded rock at vertical interface with ogee; by manual means	0.3 cycles/yd^2 of exposed face	\$ 8-12/yd^2 (one face)
Dental removal of loose, weathered, jointed, and/or bedded rock at base of ogee; by hydraulic means	0.3 cycles/yd^2 of exposed surface	\$15-30/yd^2 (base surface area)

Table 39

Conditions for Employing Baffles

Any situation where cut walls would be appropriate but where drainage through the walls is needed.

Table 40

Costs Related to Baffles

Components		Costs
Excavation into cohesionless, unconsolidated spillway substratum; 5-ft depth	Formwork required	\$25-50/yd^2 face area, one side
Placement of drain septum and reinforced-concrete wall	Formwork required	\$55-70/yd^2 face area, one side

PART IV: CONCLUSIONS AND RECOMMENDATIONS

127. REMR research at WES has established that remediation of emergency spillway erosion damage is a relatively new, but major concern to CE Districts and to other dam owners and operators. The REMR work unit conducting the current investigation has identified numerous CE and other Federal, institutional, and private-sector dams that have experienced erosion damage in their unlined spillway channels (Cameron et al. 1986). However, only a few projects have implemented or planned remedial and/or preventive measures.

128. Potentially useful remedial engineering techniques include cement-based methods such as grouting, shotcrete, soil cement/rollcrete, and high-strength unreinforced and reinforced concrete as well as rock bolts, wire mesh, gabions, and riprap. Potentially useful erosion preventive measures include construction of energy dissipators, cutoff walls, and the removal of vegetation and other obstacles to flow. Flow rerouting, the relief of uplift pressures, and the placement of geotechnical and natural grasses (especially in poorly lithified rocks and soils) may also offer useful alternatives. The majority of these remedial techniques have been utilized previously in various erosion protection schemes (e.g., streambanks, canals, levees, etc.); however, their use in unlined emergency spillway channels has not been extensive and there is little documentation available. The selection of a particular remedial technique will depend upon site conditions and costs which are highly variable for a given method.

129. The present study established a need for more published documentation of performance and effectiveness of remedial measures as well as efforts to predict rock erosion in emergency spillway channels by the use of erosional indices. It is believed that case histories, evaluations and force rankings based on erosional indices have been written on the successful and unsuccessful application of a variety of remedial technologies. However, many of these reports are unpublished and, therefore, not readily available.

Conclusions

130. Remediation design is highly site-specific, must be cost-effective, address public safety, and provide continued reservoir operations for its intended use.

131. Selection of appropriate remedial measures is complicated by hydraulic design variables, geotechnical conditions, public safety, downstream impacts, and Congress-mandated purposes of the reservoir.

132. There is a need to produce documentation relating to the performance of remedial techniques already chosen and implemented in emergency spillways and channels which have experienced erosion damage or where such damage is anticipated.

133. An important option in emergency spillway and channel remediation, not always available in most other engineering projects, is that the remedial measure or structure need not be permanent, especially in those spillway channels which only rarely experience flow events. Thus, the "impermanent structure" is a viable remedial option in some cases.

134. Physical and numeric model studies are useful when remediation design involves high-cost measures. These studies have an advantage in that many combinations of parameters can be tried for a relatively small expense, especially if numerical models are being used. However, the effectiveness of model studies is a function of thorough hydrologic, hydraulic, and geotechnical characterization of the site under consideration. Models should not be considered if input parameters are poorly known or if time and money constraints do not allow for proper model design and use.

135. Selection of remedial technique(s) must be established by site-specific characterization of the rocks forming an unlined spillway channel in terms of rock composition(s), hardness, structure and stratigraphic discontinuities, and precursor erosion elements--all of which determine rock erodibility and its rate.

136. Erosion probability indices based on methods which combine rock-mass parameters (composition, hardness, structural discontinuity, etc.) which determine "rippability," with lithostratigraphic continuity, may allow for site prioritization in terms of the need for remedial and preventive techniques.

137. Suitable remedial engineering can be designed for virtually every spillway but in most cases will retain an element of uncertainty as relates to the factor of safety in achieving remediation goals. This uncertainty relates to the characterization of site geotechnical factors and the selection of design-related variables. These factors, strength, abrasive resistance, and

chemical stability of remediated earth materials must be determined in terms of the hydraulic stresses generated by spillway overflows.

138. Natural grasses combined with geotextiles may provide cost-effective erosion prevention in emergency spillway channels excavated in soft, poorly indurated, rock strata and soils.

Recommendations

139. Compile a list of varied remediated unlined spillway channels on a nationwide (or even worldwide) basis. Document the erosion damage caused or anticipated. These spillway channels should then be monitored for performance of remediation during future flow events. It is suggested that preflood and postflood photographs and videos be used to provide visual documentation of the performance of remediation employed.

140. Review, periodically by WES, research currently being conducted by CIRIA in the United Kingdom on the performance of natural and geotextile grasses in providing cost-effective erosion prevention in some unlined spillway channels.

141. Conduct detailed site-specific studies in selected Districts to test the validity of EPI (both geotechnical and hydraulic) derived from combining "rippability" with lithostratigraphic continuity factors as well as hydraulic factors. If valid, this approach should then be employed by Districts to prioritize unlined channels in terms of remedial or preventive engineering works. These site-specific studies should also be directed toward developing methods for calculating factors of safety.

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